KINEMATICS AND FORCE CHARACTERISATION OF A KNIFEFISH-INSPIRED MECHANICAL PROPULSOR

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Abstract

The knifefish is a weakly electric eel that propels itself by passing waves along a median fin extending ventrally from jaw to tail. To study the forces generated by this fin, we built an undulating propulsion mechanism that mimics the waves passed along the biological fin using several crank-actuated fin rays.

In this paper we explore the forces created by the fin and its performance as a propulsor when mounted on a floating pontoon. Thrust in the fish seems to be improved by increasing the amplitude of the wave as it travels along the body. Using our mechanism we look at the limit of thrust production. We proceed by iterative prototyping to optimise the magnitude and along-axis directionality of the mechanism's thrust production.

1. Introduction

Animals that propel themselves underwater have been studied for many years as a path to more efficient aquatic propulsion for both remotely controlled and autonomous vehicles. The benefits are thought not only to lie in efficiency but also manoeuvrability, improved stealth and the mitigation of environmental damage.

The knifefish propels itself through the water by passing waves along the anal fin – the fin that runs along the ventral of the body, from jaw to tail, along the body midline. This fin is made up of a series of actuated spines joined by a flexible membrane. Each spine is actuated out of phase to produce waves on the fin. Water is passed back along the fin and it is this momentum transfer that is responsible for thrust. The knifefish is negatively buoyant but by creating waves from both ends of the fin that meet in the middle, the knifefish can direct water downwards and hence create upwards thrust. This allows the fish to translate in four directions, making it very manoeuvrable.

At the University of Bath, inspiration has been taken from the knifefish in order to produce a mechanical fin, known as the WaveDrive. The fin has been used as a basis for student projects so has been subject to an iterative design approach. In this paper, we describe the WaveDrive, a mechanical fin propulsor, whose inspiration has been taken from the knifefish. The propulsor has been used as a basis for several student projects and so has been subject to an iterative design approach. The first results relating to the performance of the propulsor are presented here.

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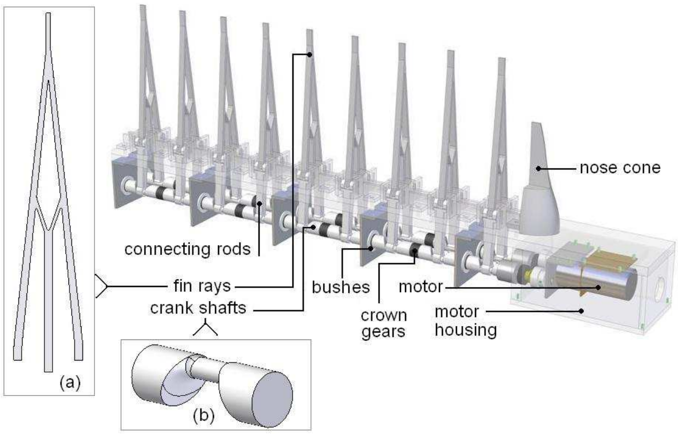

Figure 1 - CAD drawing showing the principal elements of the WaveDrive, insert (a) shows the design of the fin ray and insert (b) shows a crank shaft section

2. Design

The fundamental concept of the WaveDrive (Figure 1) is that two out of phase crank shafts actuate the compliant fin rays (Figure 1a). Angular offsets between subsequent fin rays allow waveforms to be created and thrust to be generated.

2.1 Power and Transmission

An electric motor is connected through a reduction gearing to the twin crank shafts. Each shaft has nine sections connected by crown gears. Each shaft section (Figure 1b) is machined from aluminium and has an offset crank that displaces the fin rays. Each shaft is mounted in plastic sleeve bushings at four places along its length. Connecting rods attach the offset cranks to the fin rays, the actuated ends of which are constrained to travel only in the vertical axis.

2.2 Fin rays

The original shape of the fin rays was taken from Trease et al. (2003) who sought to optimise the topology of a compliant section in order to prevent over-redundant design. The result was a triangular fin, the central portion of which was a Y-beam (Figure 1a). In the original paper only one side of the mechanism was designed to be actuated, whereas both sides are actuated antagonistically in our model. In the current design iteration the Y-beam has been moved nearer the tip. This reduces the stress in the central beam which was proving susceptible to failure.

A rapid prototyping machine was used to create models of the fin rays in order to create a negative mould. The fin rays were then cast using Polyurethane Fast Cast resin (Tomps, Sutton Bridge). This resin was selected for its ease of use: although the pot life is very short (in the order of 3 minutes), it is very fluid and so does not require degassing in a vacuum chamber and pours into moulds easily. In most of the cast parts, small defects were apparent where bubbles had been present in the mould. As the defects were small they did not interfere significantly with the properties of the fin rays.

2.3 Skin and Attachments

To convert the lateral displacement of the fin rays into a travelling wave which could create thrust, a thin, flexible elastic latex membrane was stretched over the rays and glued to them using cyanoacrylate adhesive. The rounded nose cone and thin flexible tail section introduce asymmetry and hence ensured directionality of the waveform.

3. Methods

The propulsive performance of the WaveDrive was quantified by measuring the bollard thrust produced at increasing input power for different crank configurations.

The WaveDrive was mounted in a Styrofoam pontoon and placed in a water tunnel. The stern end of the pontoon was attached to a hanging mass via a pulley. Mass was added and the motor voltage increased until the WaveDrive was just able to lift the weight. Next, the pontoon was untethered from the mass and was allowed to travel the length of the water tunnel. This series of tests was repeated for different phase angles between the crankshaft elements so that a different number of waves were apparent on the fin, shown in the inset diagram in Figure 2.

4. Results and Discussion

The initial measurements of bollard thrust are small compared with the power input since the motor input power was heavily influenced by the phase angle of the fin elements, needing more power when there were many fin rays under full bend i.e. at 90º. Thus the crankshaft speed was chosen as the independent variable and the change in thrust generated is shown for the three configurations in Figure 2. Thrust measurements were also made up to 0·96N but these are not presented as the measurements were only conducted once rather than five times as for the presented data. The graph shows the variation in thrust for a given crank shaft speed. It is intuitive that a faster crankshaft speed will result in a larger thrust force and this is what we see on the graph. What is less intuitive, perhaps, is the effect of crank element phase angle on the thrust produced. We find that for a given crank speed, the trend is for higher thrust at lower phase angles.

The range of velocity attained was from 4 - 8 cms^{-1} for all phase angles, dependent on the crankshaft speed.

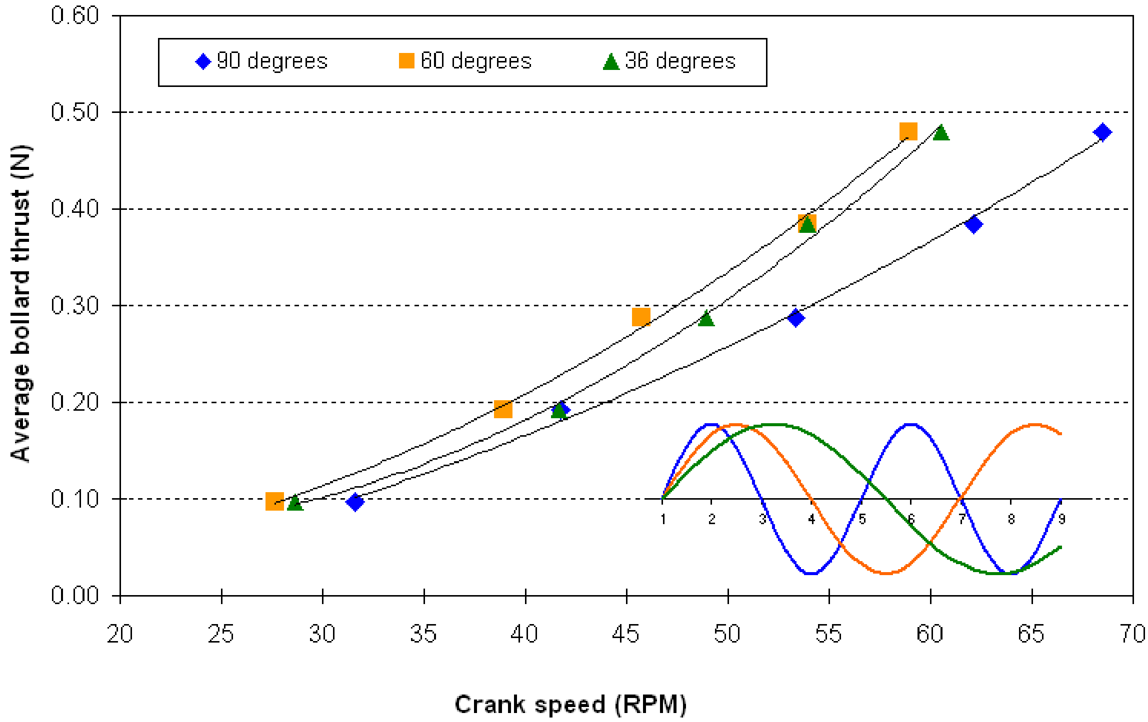

Figure 2 – Bollard thrust of the WaveDrive as a function of the crankshaft speed for three phase angles, the inset diagram shows the waveforms generated at each phase angle with the number corresponding to the fin ray numbers

5. Conclusions and Further Work

The initial results imply that there is an optimum configuration for the WaveDrive but further testing is necessary to locate this optimum. In order to properly relate motor power to thrust generation it will be necessary to quantify the power used by the motor just to bend the fin rays. Once this has been measured, we will be able to show how changes in input power relate to changes in thrust. We also hope to quantify the hydrodynamic efficiency of the different configurations.

6. References

Trease, B. P., Lu, K.-J. and Kota, S. (2003). Biomimetic Compliant System for Smart Actuator-Driven Aquatic Propulsion: Preliminary Results. *Proceedings of IMECE2003 2003 ASME International Mechanical Engineering Congress.*

7. Acknowledgements

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